GPS Solut (2010) 14:83–89
DOI 10.1007/s10291-009-0129-0

ORIGINAL ARTICLE

Seismo-ionospheric precursor of the 2008 Mw7.9 Wenchuan earthquake observed by FORMOSAT-3/COSMIC

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Received: 23 January 2009 / Accepted: 18 May 2009 / Published online: 9 June 2009

Abstract The seismo-ionospheric precursor prior to the Mw7.9 earthquake near Wenchuan, China, on 12 May 2008 was observed by the FORMOSAT-3/COSMIC satellite constellation. By binning radio occultation observations, the three-dimensional ionospheric structure can be obtained to monitor the ionospheric electron density variation prior to the earthquake. It has been determined that near the epicenter the F2-peak height, hmF2, descends about 25 km and the F2-peak electron density, NmF2, decreases about 2×10^5 el/cm^3 around noon within 5 days prior to the earthquake. The integrated electron content decreases more than 2 TECU between 250 and 300 km altitude.

Keywords FORMOSAT3/COSMIC · Ionosphere · Earthquake · Satellite · GPS · Radio occultation

Introduction

Electric, magnetic, electromagnetic, or luminous phenomena associated with seismic activities have been extensively discussed in the literature (Hayakawa and Fujinawa 1994; Hayakawa 1999; Bolt 1999; Freund 2000; Hayakawa and Molchanov 2002). Discussions of seismo-ionospheric phenomena in the ionospheric peak density as observed by ionosonde radars and the total electron content (TEC) as derived by ground-based global positioning system (GPS) receivers prior to large earthquakes can be found in Liu et al. (2000, 2001), Hayakawa and Molchanov (2002), Pulinets and Boyarchuk (2004), Kamogawa (2006) and Rishbeth (2006). Liu et al. (2000) have examined variations of the plasma frequency at the F2-peak, denoted by foF2, recorded by a local ionosonde during 14 earthquakes of magnitude $M \geq 6.0$ in the Taiwan region during the 6-year period of 1994–1999. They found that the ionospheric foF2 value decreased anomalously by 3–5 MHz (20–33% of the reference value) in the afternoon period of 1200–1700 LT for 1–5 days before earthquakes. The TEC derived from ground-based GPS receivers correlates well with the foF2 recorded by a co-located ionosonde, and can be used to observe the pre-earthquake ionospheric anomalies (Liu et al. 2001, 2004a). Chen et al. (2004) and Liu et al. (2006) statistically investigated the foF2 variations associated with 184 $M \geq 5.0$ earthquakes in Taiwan during 1994–1999, and defined the pre-earthquake ionospheric anomaly (PEIA) as a significant decrease of foF2 during the afternoon period 1200–1800 LT within 1–5 days before the earthquakes. They further demonstrated that the likelihood of earthquakes following PEIA increases with increasing earthquake magnitude but decreases with increased distance from epicenter to the ionosonde station. Liu et al. (2008) examined foF2 values recorded by a digital portable sounder and TEC obtained by a network of eight GPS receivers scattered over the island before the Pingtung earthquakes, and found a reduction of about 7 TECU (30% of reference value) with a duration of 4.5 h. They showed that ionospheric foF2 and GPS TEC around the epicenters abnormally reduce in the afternoon 4 days preceding the earthquakes.

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The Constellation Observing System for Meteorology, Ionosphere, and Climate (FORMOSAT-3/COSMIC or F3/C for short), consists of six microsatellites, designed to monitor terrestrial and space weather (Rocken et al. 2000). Its GPS occultation experiment (GOX) instrumentation performs radio occultation observations in the atmosphere and the ionosphere in particular. Each microsatellite operates a tri-band beacon (TBB) transmitter to perform ionospheric tomography and a tiny ionosphere photometer (TIP) to observe the nighttime ionospheric airglow emission. The constellation of six microsatellites was launched into an initial low-earth circular orbit at an altitude of 512 km and 72° inclination (Cheng et al. 2006) on 15 April 2006. The full mission orbit of about 800 km altitude, 72° inclination, and 30° separation in longitude was achieved 18 months later. Since completion of the orbital deployment in November 2007, the GOX instruments observe about 2,500 vertical ionospheric electron density profiles daily with a reported accuracy of 10^4–10^5 el/cm^3. These profiles are globally and uniformly distributed. Using such a globally dense set of occultation observations, the three-dimensional ionospheric electron density can be constructed in a timely manner.

On 12 May 2008, an Mw7.9 earthquake struck Wenchuan (31.0°N, 103.4°E, depth 19 km) at 1428 LT. Liu et al. (2009) examined the global ionospheric map (GIM, ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex), GPS TEC and F3/C ionospheric vertical profile for the time prior to the earthquake. They found that the GPS TEC decreases in the afternoon for days 6–4 before the earthquake and that the ionospheric peak density derived from F3/C profiles significantly decreases (as GPS TEC anomalously reduces). In this paper, we employ the three-dimensional electron density structure constructed by FORMOSAT-3/COSMIC observation to further investigate the ionospheric anomalies before the Wenchuan earthquake.

FORMOSAT-3/COSMIC observations and interpretation

Data from the World Data Center for Geomagnetism in Kyoto (http://swdcwww.kugi.kyoto-u.ac.jp) show that it was in general geomagnetically quiet 20 days prior to the Wenchuan earthquake except for a magnetic disturbance

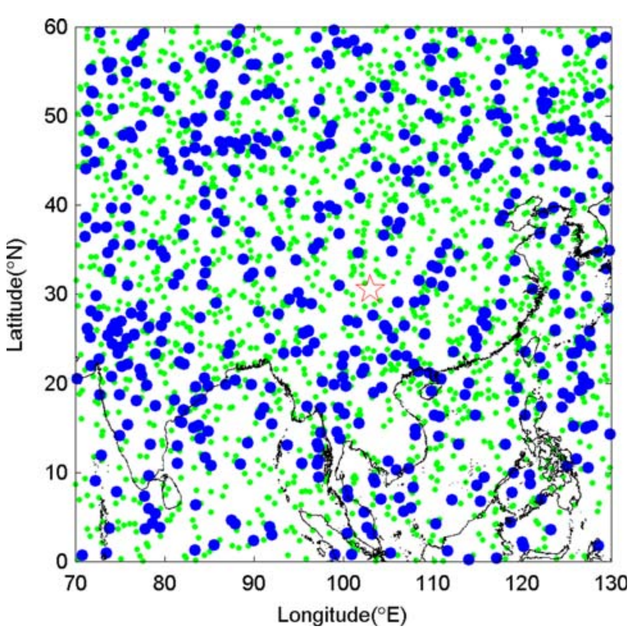

Fig. 1 The location of 2402 occultation data points observed by F3/C within 20 days prior to the earthquake. The *green* and *blue dots* represent the occultation data observed within 22 April–6 May and 7–11 May, respectively. The epicenter of Wenchuan earthquake is denoted by *pentagram* symbol

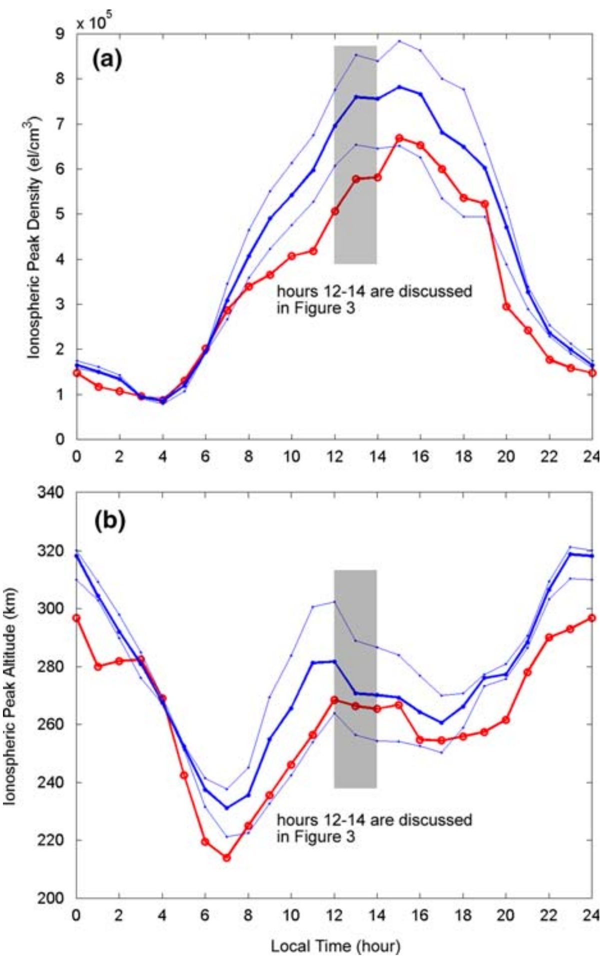

Fig. 2 The temporal variation of **a** ionospheric peak density and **b** peak altitude derived from the ionospheric vertical profile within ±10° from the epicenter within reference (*bold blue*) and observed (*bold red*) period, respectively. The lower and the upper quartiles (*thin blue*) are employed to describe the spread of data within reference period

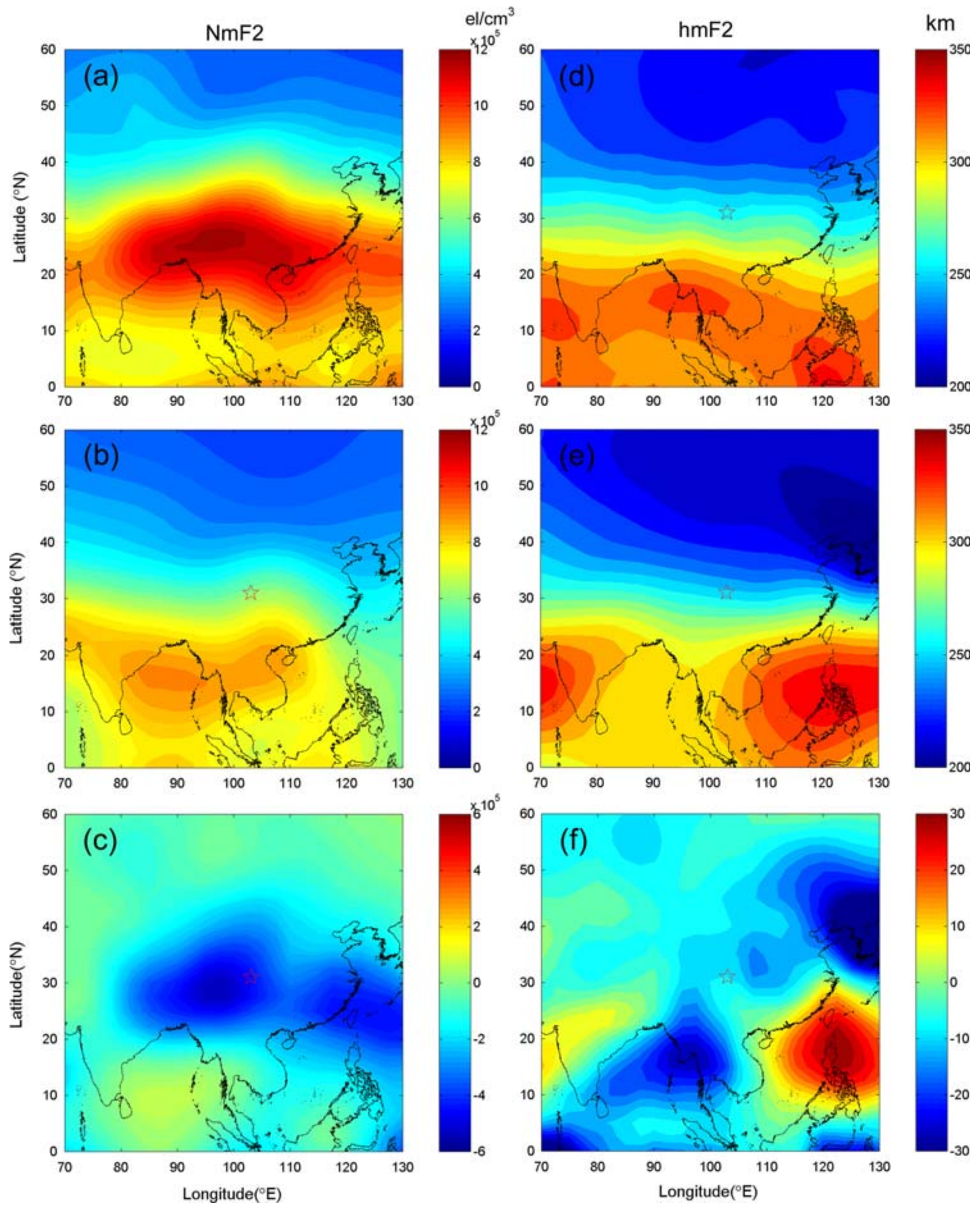

Fig. 3 The ionospheric peak density NmF2 and peak altitude hmF2 map observed between 1200 and 1400 LT by F3/C. The NmF2 maps of **a** reference period (22 April–6 May), **b** observed period (7–11 May) and **c** the difference **b** − **a**. The hmF2 maps of **d** reference period, **e** observed period and **f** the difference **e** − **d**

on 23 April. Based on previous studies (Liu et al. 2000, 2001, 2004a, b, 2006; Chen et al. 2004; Hsiao et al. 2008), we examined the ionospheric anomaly of the Wenchuan earthquake by comparing the observed electron density for 1–5 days before the earthquake (7–11 May is the observed period) with the associated 6–20 reference days (22 April–6 May is the reference period) before the earthquake.

Since the completion of the F3/C constellation deployment, the GOX observations are distributed uniformly. Figure 1 shows the epicenter of the Wenchuan earthquake, and the location of 2402 occultation data points in the region 0–60°N and 70–130°E with 1882 and 520 data points belong to the reference and observed periods, respectively. The Abel integral transform and three-dimensional constrained GPS radio occultation inversion algorithms were used to invert the F3/C occultation soundings and have been validated with critical frequency data from ionosonde stations and with TEC data from GPS ground receivers. The detailed description of the technique applied to invert the F3/C occultation soundings to ionospheric electron density profiles are given by Schreiner et al. (1999) and Syndergaard et al. (2006). Some validation studies of the F3/C radio occultation observations have been carried out by Schreiner et al. (2007) and Lei et al. (2007), showing that the electron density profiles retrieved from F3/C radio occultation data are in agreement with incoherent scatter radar and ionosonde measurements.

We examined both the ionospheric peak density (NmF2) and the peak altitude (hmF2), derived from the ionospheric vertical profile, within ±10° from the epicenter and computed the median value hourly in a sequence of local time intervals within the reference and observed periods (Fig. 2). In order to describe the spread of estimates, we calculate the lower and upper quartiles of NmF2 and hmF2 within ±10° from the epicenter by using the technique of Liu et al. (2000, 2001, 2004a, 2006). The peak density of the observed period is lower than the median value of reference period, except 0300–0600 LT. Furthermore it is lower than the lower quartile, except 1500–1900 LT. The maximum deviation of about 2×10^5 el/cm^3 occurred between 1200 and 1400 LT. The peak altitude descends starts at 0500 LT with a maximum deviation from the reference of about 25 km around 1100 LT. However, the peak altitude of the observed period is lower than the lower quartile only within 0500–0700 LT and 1800–0200 LT. In general, the peak density and altitude in the observed period are lower than those in the reference period.

In order to understand the larger spatial distribution of the plasma variation, we construct contour maps of ionospheric peak density and peak altitude by binning measurements during the reference and observed periods, and taking median values of observations located in a 2.5° × 2.5°× 1 km (longitude × latitude × altitude) grid resolution. Figure 3a, b, d, e show the map of peak density and peak altitude obtained within 1200–1400 LT during the reference and observed periods, respectively. It can be seen that the NmF2 significantly decreases (at least 3×10^5 el/cm^3 in 20–40°N and 85–105°E, and 6×10^5 el/cm^3 around the epicenter location 30°N and 98°E) and the hmF2 descends (along 33°N and 97°E) around the epicenter within 1–5 days before the earthquake (Fig. 3c, f).

We further integrate the electron content of each radio occultation profile from 150 to 450 km altitude within the two periods and construct the image of integrated electron content, hereafter referred to as IEC(150–450). Similarly, we compute the deviation of IEC(150–450) from the reference period and find that the IEC(150–450) anomalously reduces (at least 6 TECU in 25–35°N and 85–105°E, and 8 TECU around the location 29°N and 98°E) before the earthquake (Fig. 4).

In order to investigate electron density differences between observed and reference periods, we subdivide the IEC shown in Fig. 4 into six 50 km altitude intervals covering the 150–450 km altitude range (Fig. 5). The IEC(150–200) increases slightly above the epicenter, however above 200 km altitude IEC(200–250), IEC(250–300), IEC(300–350), IEC(350–400), and IEC(400–450) decrease around the epicenter. The integrated electron content decreases more than 2 TECU around the epicenter at 250–300 km altitude and significantly decreases around the location 30°N and 96°E. There is no significant deviation of the electron content between 450 and 800 km.

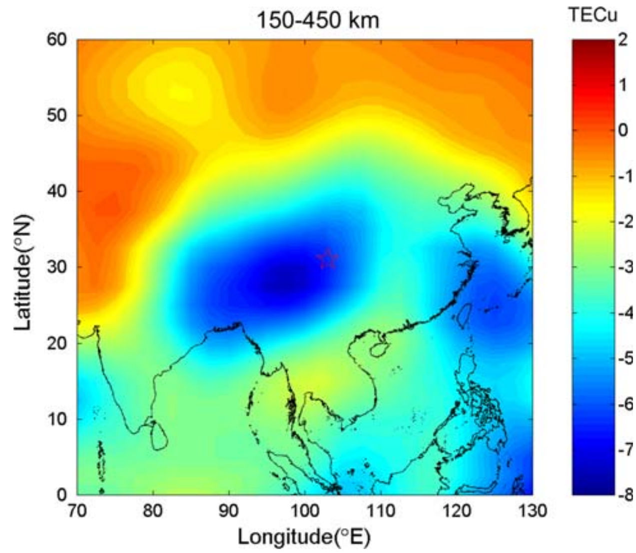

Fig. 4 The difference of integrated electron content between the observed and reference periods in the 150–450 km altitude range, as derived from F3/C electron density observation for 1200–1400 LT. 1TECU = 10^{12} el/cm^2

Similar to Fig. 2, the time variations of IEC as a function of altitude within region ±10° from the epicenter are shown in Fig. 6. The reduction of ionospheric electron density begins around 0700 LT and mainly occurs from 250 to 400 km, with the most pronounced deviation occurring in the 250–300 km altitude range. The enhancement of electron density from 150 to 200 km also can be seen between 1000 and 1100 LT.

Discussion and conclusion

The FORMOSAT-3/COSMIC radio occultation measurements observe the ionospheric vertical density profile from about 100 km to the satellite orbital height of 800 km. Other methods are more limited: the ionosonde radar observes the virtual height variation below the ionospheric peak altitude, and the ground-based GPS receiver derives the total electron density. The anomalous features in NmF2 and IEC(150–450) before the Wenchuan earthquake, as observed by F3/C radio occultation soundings, are in good agreement with the previous results obtained from ionosonde foF2 and GPS TEC (Liu et al. 2000, 2001, 2004a, b, 2006, 2008; Chen et al. 2004), i.e. decreasing in the afternoon period of 1200-1800 LT within 1–5 days before the earthquakes.

Hsiao et al. (2008) examined the ionospheric anomalies of the 26 December 2006, M7.0 Pingtung earthquake doublet, which occurred when the constellation deployment of F3/C was not yet completed; the occultation data in the afternoon period near the epicenter were available

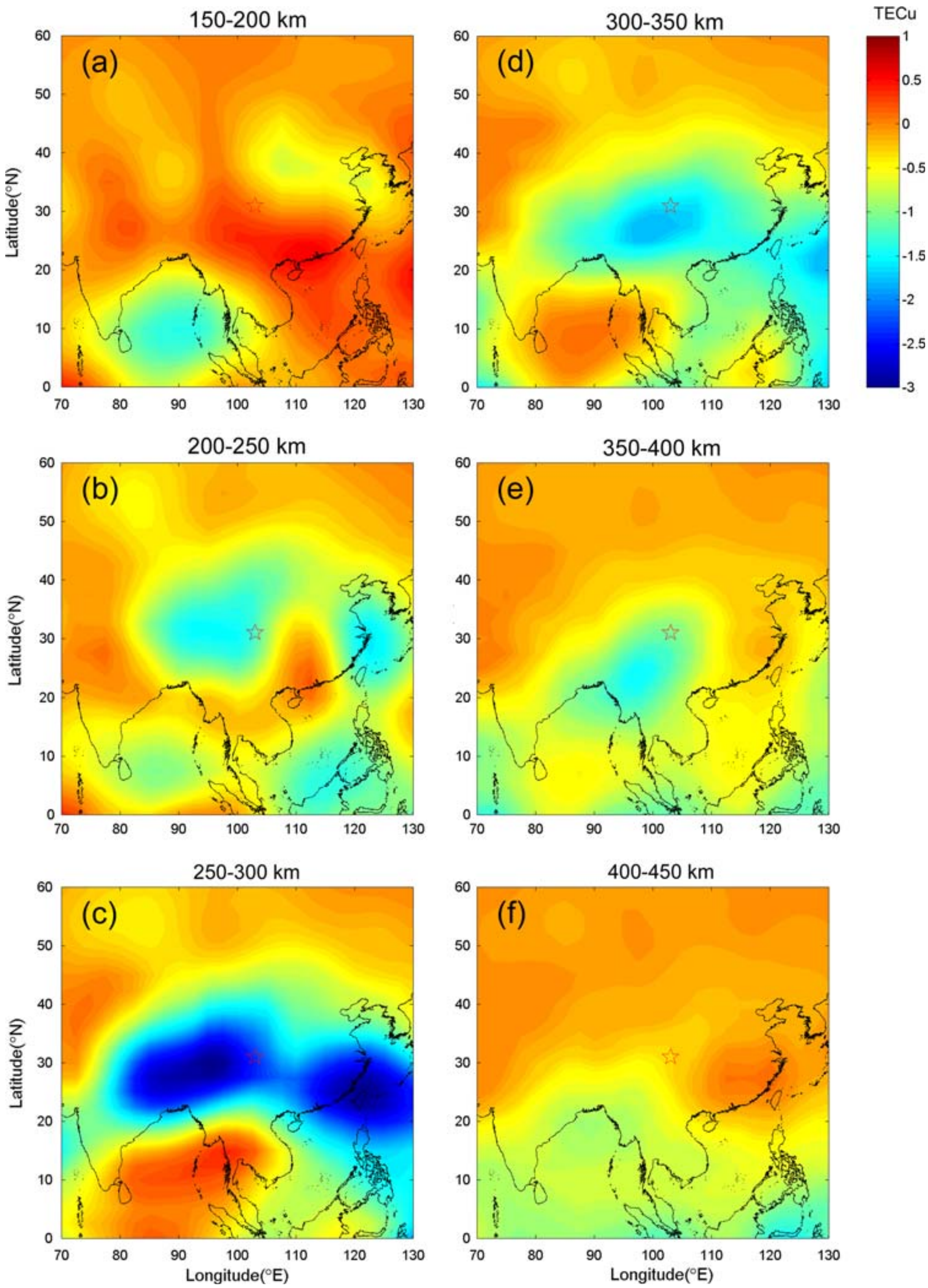

Fig. 5 The difference of integrated electron content between the observed and reference periods at every 50 km altitude interval in the 150–450 km range as observed by F3/C during 1200–1400 LT

only between 1200 and 1500 LT. Since the completion of the constellation in November 2007, a sequence of electron content time series can be obtained by computing the median of uniformly distributed occultation measurements in different spatial and temporal resolutions. Around the epicenter of Wenchuan earthquake, the deviation of the ionospheric peak density between the observed and the reference periods reaches the maximum between 1200 and 1400 LT. The significant reduction also could be observed prior to Pingtung earthquake in the same local time interval. The enhancement of ionospheric electron density within the lower altitudes (Pingtung, 150–250 km, Wenchuan, 150–200 km) can be observed before these two earthquakes.

Liu et al. (2009) examined the F3/C vertical profiles before the Wenchuan earthquake and observed that the reduction anomaly of ionospheric peak density also appears in day 6 prior to the earthquake. Since the median

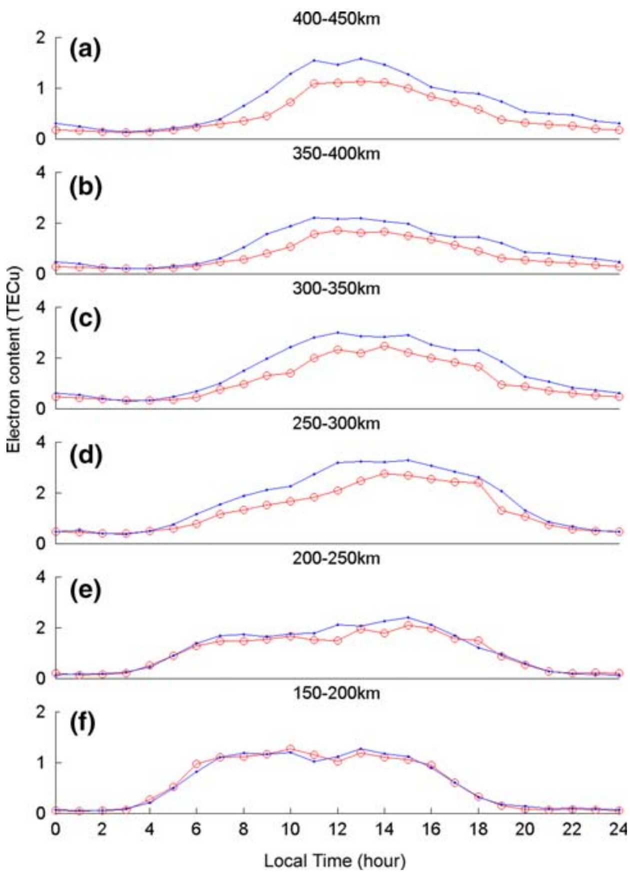

Fig. 6 Temporal variation of integrated electron content at every 50 km altitude interval from 150 to 450 km altitude within the reference (*blue*) and observed (*red*) periods. Note the change in scale for parts **a** and **f**

value of reference (15 days) and observed (5 days) period were adopted to examine the ionospheric anomaly in this study, the reduction in day 6 prior to the earthquake has no influence in the reference and electron density of the observed period still deviates from the reference. The reduction anomaly still occurs mainly in the observed period, which is consistent with previous studies (Liu et al. 2000, 2004a, b, 2006; Chen et al. 2004). Meanwhile, the finding that the ionospheric peak altitude generally descends within 5 days prior to the earthquake also agrees with Liu et al. (2009).

After completion of the FORMOSAT-3/COSMIC constellation deployment in November 2007, the three-dimensional ionospheric image constructed by globally and uniformly distributed radio occultation measurement provides unprecedented detail of ionospheric anomalies prior to the earthquakes.

Acknowledgments The authors thank the FORMOSAT-3/COSMIC operation team in National Space Organization (NSPO) for operating the satellite constellation. NSPO is supported by the National Science Council of Taiwan. The authors wish to thank the editor and reviewer for their constructive comments and useful suggestions.

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